TIME AND FREQUENCY ACTIVITIES AT THE NATIONAL PHYSICAL LABORATORY

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Abstract

The Time and Frequency Section of the National Physical Laboratory (NPL) has an active program of work in time and frequency metrology. This paper provides an overview of this section's principal activities. These include: maintenance and development of the national time scale UTC (NPL), devlopment of a new cesium fountain clock, time-transfer activities, development of clock algorithms, technology-transfer activities, and time and frequency dissemination in the UK.

INTRODUCTION

During the past four years the Time and Frequency Section of the National Physical Laboratory (NPL) has been expanding its activities and now undertakes a varied program of development work and technology transfer. This complements the section's primary role, that of the maintenance of the UK national time scale UTC(NPL). This paper will not only provide a detailed review of NPL's current Time and Frequency programme activities, but will provide some indication of possible future work.

UK NATIONAL TIME SCALE UTC(NPL)

NPL's principal role is the maintenance of an ensemble of atomic frequency standards from which the national time scale UTC(NPL) is generated. The present clock ensemble consists of two active hydrogen masers (model Sigma Tau, VLBA-112), and four cesium clocks (model Hewlett-Packard HP5701A, three high performance and one standard tube). At present the standard frequency signal originating from one of the active masers is used to generate the timescale UTC(NPL). UTC(NPL) is routinely compared against other primary time scales using a variety of satellite time transfer methods. Data form GPS common-view, Glonass, and Two-Way Satellite Time and Frequency Transfer (TWSTFT) time transfers are routinely forwarded to BIPM. The TWSTFT and GPS common-view measurements are used in the calculation of TAI. During recent years NPL's time scale has been very stable, UTC(NPL) being maintained within 100 ns of UTC. NPL plans to strengthen its clock ensemble, in particular obtaining a third active hydrogen maser and additional cesium standards. UTC(NPL) is steered by adjusting the Hydrogen Maser output frequency. The interval between steers is usually in excess of 100 days.

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DEVELOPMENT OF A CLOCK ALGORITHM

In recent months NPL has been actively developing a clock algorithm to provide a real-time realization of UTC(NPL), based on a weighted average of all of NPL's clocks. This should improve both the integrity and the stability of the time scale. The algorithm is based on NIST's AT1 clock algorithm; this has, however, been modified to meet NPL's own requirements. A plot showing the algorithm's clock weight parameters is shown in Figure 1 (Clock data supplied by USNO with NPL analysis). Research work is continuing, particularly in the area of understanding correlated clock noise. One possibility is to include remote clocks into the clock ensemble in order to improve the medium-term stability, and to provide an ensemble timescale against which to compare the cesium fountain.

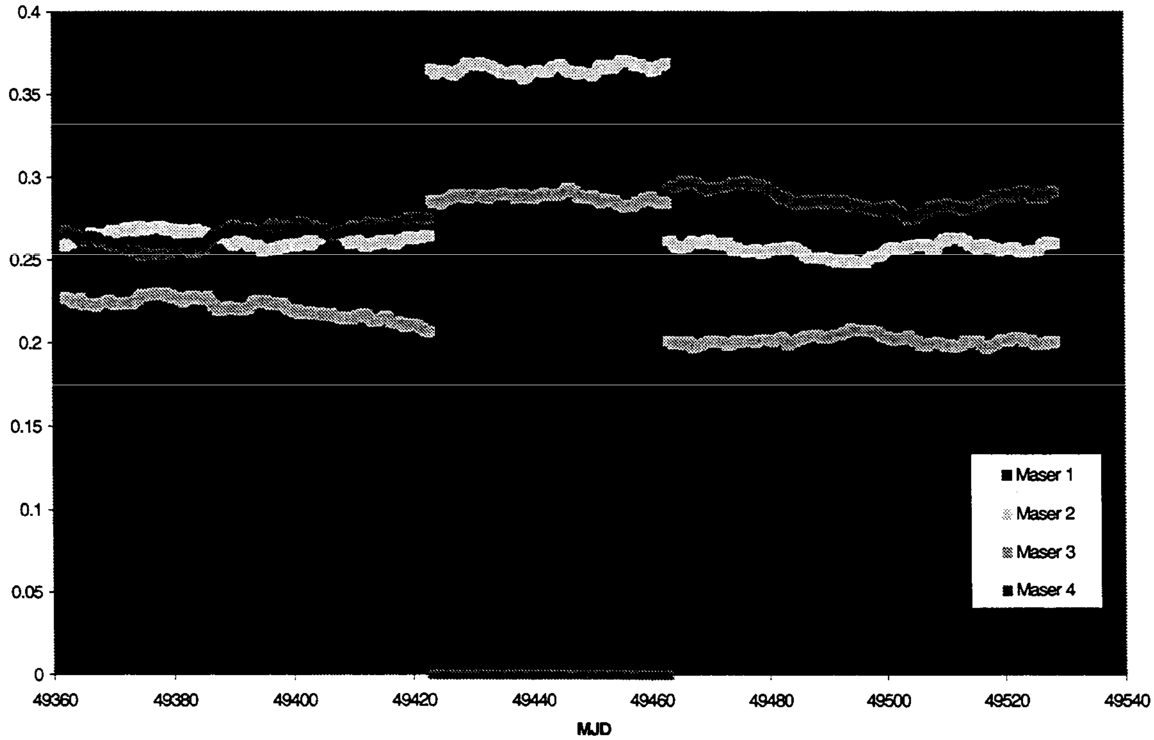

Figure 1: Changing clock weights during the operation of NPL's clock algorithm using 167 days of clock data. Maser 4 has been removed from the ensemble between MJD 49422 and 49462.

DEVELOPMENT OF A CESIUM FOUNTAIN CLOCK

An experimental cesium fountain frequency standard, known as F1, has been constructed at the NPL. Although not intended to operate as a primary frequency standard in its present form, this fountain is being used to provide experience and evaluate systems that will contribute to the design of a primary frequency standard. It has been operated routinely over many months, and Ramsey fringes have been observed and some causes of frequency shifts have been investigated. Figure 2 shows a typical Ramsey fringe pattern. Each point represents a single fountain cycle - there is no averaging - and the microwave frequency is stepped by 0.05 Hz between cycles. The central fringe width is 1.2 Hz.

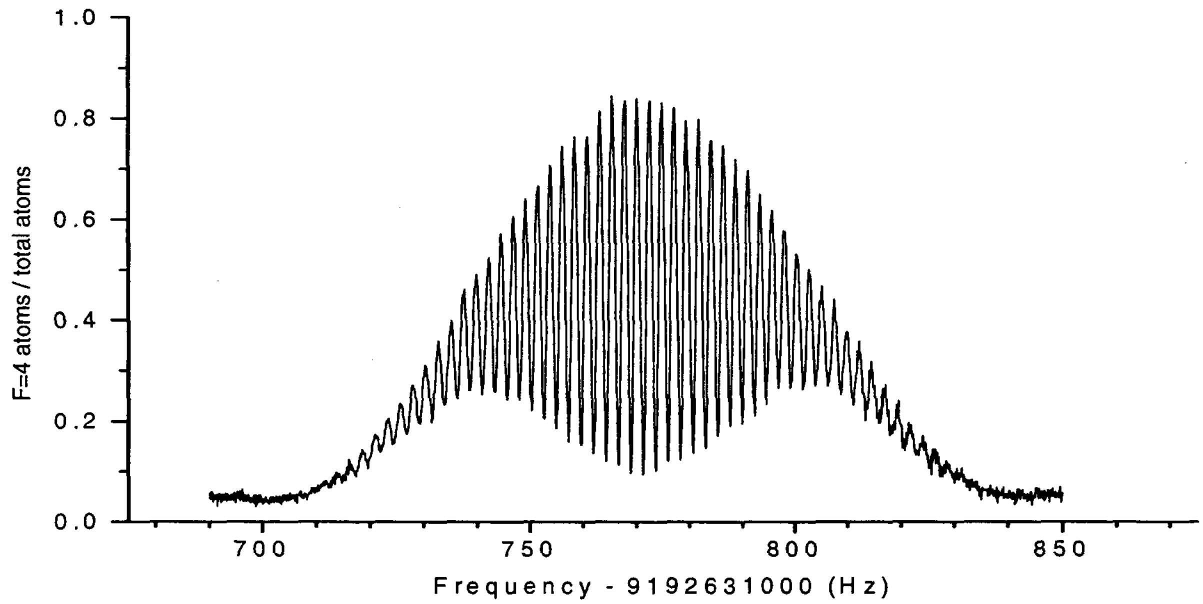

Figure 2: Ramsey fringe pattern generated from NPL's cesium fountain.

The experimental fountain is configured with the trapping and cooling region in the center, between the C-field chamber and the detection region. The C-field chamber containing the TE_{011} microwave cavity is of titanium. It is enclosed within three layers of mu-metal magnetic screens, with a fourth layer surrounding the entire vacuum system, and field compensation coils are also provided. The six cooling laser beams are arranged in an xyz geometry. They are generated by a pair of slave lasers injection locked to light from an extended cavity master laser. An additional laser, a DBR diode, provides repumping light. Polarizing fibers give spatial filtering of the beams, as well as decoupling the alignment of the frequency control optics from that of the optics around the vacuum chamber. After launching in F=4, a proportion of the atoms are transferred to the F=3, M_F=0 level by a microwave pulse, then atoms remaining in F=4 are removed by an optical pushing pulse. Following the double pass through the microwave cavity, the relative populations of both ground-state levels are detected by optical pumping and fluorescence detection. The sequencing of the repeated fountain cycle is under computer control to allow the operating parameters to be readily optimized.

Because of the pulsed operation of the fountain, the source of microwaves at 9.192 GHz must have low phase noise, particularly close-to-carrier noise in the range of 0.1 to 10 Hz offset. The scheme adopted uses a dielectric resonant oscillator phase locked in an offset scheme using a sampling down-converter and a synthesizer with millihertz resolution. The sampling down-converter is driven by a 200 MHz source derived from a pair of phase-locked low noise crystal oscillators, at 5 and 100 MHz. The 5 MHz crystal is in turn loosely phase-locked at 100 MHz to the local timescale frequency reference, an active hydrogen maser.

In parallel with the work on F1, a second cesium fountain, named F2, is under construction at the NPL. A major design consideration is that its sources of frequency shifts can be measured and corrected for, and it is intended that it will ultimately operate as a primary frequency standard. The interaction chamber is being constructed from aluminium alloy and other components will utilise low-permeability materials. In the design of F2 the trapping chamber is located below the detection region, and the three pairs of cooling beams enter the chamber via optical fibers at 35.3° to the horizontal, in the (111) geometry. The central detection chamber has four large-diameter windows for the detection beams and fluorescence detection optics, as well as ports for pumping and for microwave feedthroughs. Between the trapping and detection chambers is an additional small chamber with dimensions corresponding to the TE_{011} mode at 9.192 GHz for preparing the launched atoms in the F= 3, $M_F = 0$ state. The fountain primary frequency standard will be commissioned in the new NPL building, in a module which will be ready for occupation in early 2001. This will provide better temperature stability and vibration isolation than the present location, and a comparable level of ambient magnetic field.

DEVELOPMENT OF HIGH ACCURACY SATELLITE TIME- AND FREQUENCY-TRANSFER METHODS

The development of high accuracy time and frequency transfer methods at NPL has been motivated by the requirement to compare NPL's cesium fountain clock against similar clocks under development at other primary timing laboratories, and the requirement to accurately relate UTC(NPL) to UTC. NPL also wishes to use its time transfer expertise in the development of high accuracy time and frequency dissemination methods in the UK.

Two-Way Satellite Time and Frequency Transfer (TWSTFT) has been under development at NPL since 1992, and regular TWSTFT sessions began in 1993. NPL was heavily involved in the early TWSTFT work, in particular studies of closing errors observed within networks of TWSTFT stations [1]. A second TWSTFT earth station has been commissioned during 1999 and is now operational. NPL routinely participates in European and transatlantic TWSTFT measurement sessions, which are performed three times per week. During 1998 and 1999 there have been considerable efforts directed towards characterizing the earth station's performance, and improving its stability [2][3]. Figure 3 shows the data from the (UTC(NPL)-UTC(NIST)) TWSTFT link which normallyhavea stability of better than 1 ns when considering a three day averaging time. TWSTFT data from the (UTC(USNO) - UTC(NPL)) link is now being used in the computation of TAI.

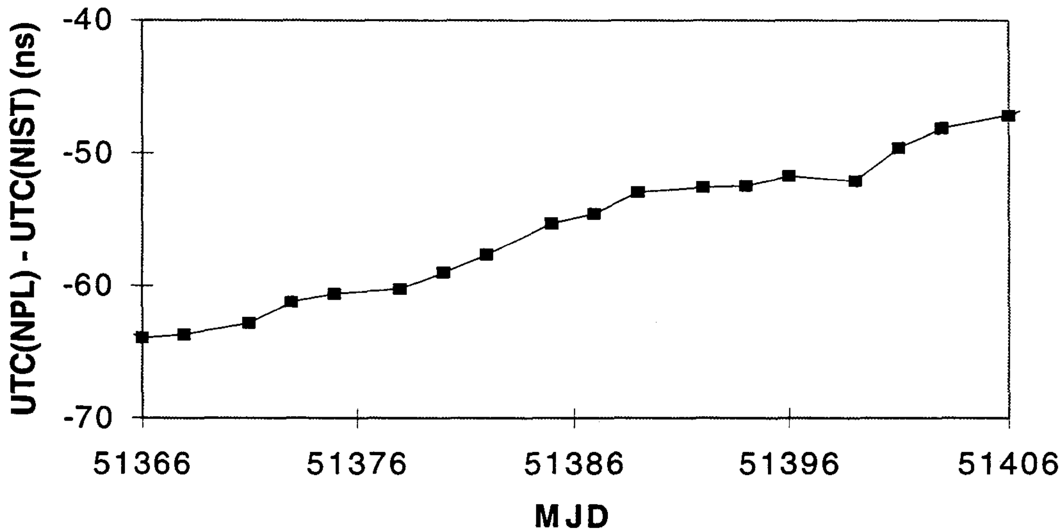

Figure 3: TWSTFT comparisons between UTC(NPL) and UTC(NIST) made over 40 days.

NPL is active in the field of geodetic GPS time transfer. This method offers the potential of continuous ultra high stability time and frequency transfers over intercontinental baselines. During 1997 NPL purchased an Ashtech Z12-T geodetic-quality GPS receiver to complement its existing TTR-4P receiver. The operation of the new receiver has been automated and NPL has been participating in international geodetic GPS time transfer experiments, coordinated by the University of Bern. Work is underway to obtain approval to operate as an International GPS Service (IGS) station. The purchase of an additional receiver is being considered. An example of the time transfers obtained between NPL and PTB is shown in Figure 4. The performance of NPL's geodetic GPS installation has been characterized [4], both for the whole time-transfer links and for the individual components of the installation. NPL has written its own geodetic GPS software to perform short-baseline common-clock experiments. This software has been used to measure the relative delay stabilities of the Ashtech Z12 and TTR-4P receivers [5]. This software is now being revised to calculate geodetic GPS time transfers over longer baselines. Initial results are promising.

NPL has been operating a multi-channel combined GPS/GLONASS receiver which is contributing to the international IGEX campaign and forwarding GLONASS common-view data to BIPM. NPL is, however, unlikely to pursue further this work until the future of the GLONASS constellation becomes more certain.

Intercomparisons are being performed between different time-transfer methods, particularly between TWSTFT, geodetic GPS time transfer and GPS common-view time transfer. NPL is examining possible method to optimally combining a group of time-transfer links. The work looks promising and presentations on the subject were made to the TWSTFT working group in December 1999. NPL has also been examining future time-transfer methods, in particular future participation in the ACES and T2L2 projects and future use of EGNOS and Galileo.

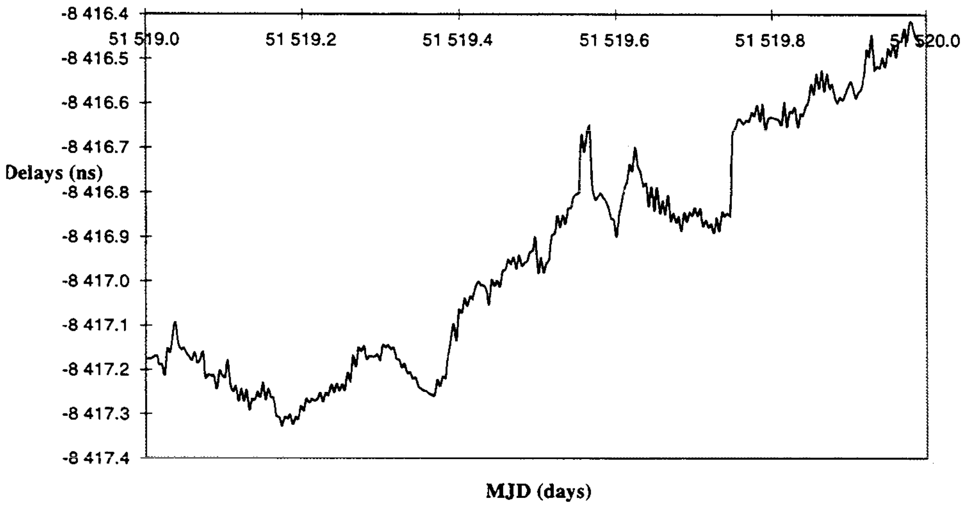

Figure 4: Geodetic GPS time transfer between NPL and PTB.

SATELLITE TIME AND FREQUENCY DISSEMINATION

The UK has a small but active community of users of high accuracy time and frequency dissemination. During 1997 NPL undertook a study of the performance of 15 GPS Disciplined Oscillators (GPSDO) [6], which provided the information base from which these devices became accepted as standards traceable to UTC(NPL). Since then NPL has been working with the United Kingdom Accreditation Service (UKAS) on the production of a GPSDO guidance document. NPL has also been developing a GPSDO characterization service.

NPL is starting to perform continuous monitoring of the GPS system, when viewed from its Teddington site. This will provide a published measure of (UTC(NPL) - GPS Time) for UK time and frequency users, and also assist in validating the integrity of the GPS signals when received at GPSDO installations traceable to UTC.

Common-view GPS time transfer has long been used inter-compare atomic clocks at primary timing laboratories. However, the relatively high cost of the GPS hardware has prevented this method from becoming more widely used amongst the UK time and frequency users. NPL has been working with a UK time and frequency manufacturer to develop a suitable inexpensive GPS common-view receiver. NPL may possibly launch a GPS common-view service, where customers may use the GPS common-view method to obtain time and frequency transfers traceable to UTC(NPL).

NPL is also looking towards the future of Global Satellite Navigation Systems (GNSS), and their use in high accuracy time and frequency dissemination, in particular examining the potential accuracies

achievable by the next generation of GNSS linked disciplined oscillators.

TERRESTRIAL TIME AND FREQUENCY DISSEMINATION IN THE UK

NPL's Rugby-based MSF 60 kHz transmissions is the principal method of time and frequency dissemination in the UK. Monitoring the phase of the MSF carrier, it is possible to perform frequency transfers with an uncertainty of 3×10^{-12} for an averaging time (τ) of 1 day. MSF provides complete coverage of the UK and may be received over much of Europe.

NPL operates a computer time service, where the user may use a time code traceable to UTC(NPL) to set for example the clock of a PC. NPL also operates both an 'on-site' NPL based and 'off-site' portable clock calibration service.

TECHNOLOGY TRANSFER

The NPL time and frequency section operates a user club, where the UK time and frequency user community may meet at least once every six months. Meetings are often held away from NPL and will involve several outside speakers. There is an extensive time and frequency WWW site which is regularly updated. Every month a bulletin is published which contains information on the MSF transmissions, and Droitwich 198 kHz standard frequency transmission. The bulletin will soon be updated to include GPS information. There is an enquiry line which handles many hundreds of telephone calls each year from the public.

CONCLUSION

This paper has provided a overview of the activities of theTime andFrequency Section of NPL.

REFERENCES

[1] J. A. Davis, P. R. Pearce, D. Kirchner, H. Ressler, P. Hetzel, A. Soering, G. de Jong, P. Grudler, F. Baumont, and L. Veenstra 1995, *"European two-way satellite time transfer experiments using the Intelsat (VA-F13) satellite at 307E,"* **IEEE Transactions on Instrumentation and Measurement, 44,** 90-93.

[2] S. L. Shemar and J. A. Davis 1999, *"A study of delay instabilities within a two-way satellite transfer earth station,"* Proceedings of a Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium, April 1999, pp. 208-212.

[3] S. L. Shemar and J. A. Davis 1999, *"Improving the delay stability of a two-way satellite time and frequency transfer earth station,"* Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-3 December 1998, Reston, Virginia, USA, pp. 329-340.

[4] J. D. Clarke, J. A. Davis, and A. J. Lowe 1999, *"Characterization of NPL's geodetic GPS time transfer receivers,"* Proceedings of a Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium, April 1999, Besançon, France, pp. 225-229.

[5] J. Clarke, J. A. Davis, and A. Lowe 1999, *"A very-short-baseline experiment using two geodetic-quality GPS receivers and carrier phase techniques,"* Proceedings of the 30th Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 1-3 December 1998, Reston, Virginia, USA, pp. 257-269.

[6] J. A. Davis and J. M. Furlong 1997, *"Report on the study to determine the suitability of GPS desciplined oscillators as time and frequency standards traceable to the UK national time scale UTC (NPL),"* NPL Report No. CTM1, October 1997.

Questions and Answers

DEMETRIOS MATSAKIS (USNO): You mentioned the term "variogram" with regards to your timescale. I wasn't sure if was designed in your next viewgraph, but could you talk more about it?

JOHN DAVIS (NPL): This is an idea that a mathematician at NPL had. It looked to be fairly similar to the Allan variance. It was an idea of being able to use a statistical function to sort out very different noise types which we could then use in our clock algorithm. It's something Benedict's trying at the moment. We don't know how well it works because it's not really been put into operation yet, but it's something we're working on.

I can come and talk to you a little bit more about it.